BNL-66811

Impedance group summary*

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The impedance working group was charged to reply to the following 8 questions relevant to the design of high-intensity proton machines such as the SNS or the FNAL driver. These questions were first discussed one by one in the whole group, then each one of them assigned to one member to summarize. On the last morning these contributions were publicly read, re-discussed and re-written where required - hence they are not the opinion of a particular person, but rather the averaged opinion of all members of the working group.

1) **High intensity rings require large apertures. Are impedance calculations reliable for large vacuum chambers, large steps, and large aperture kicker magnets?**

- No problems for large steps or vacuum chambers (dimensional scaling).
- With advances in analytical and numerical methods these problems are well understood.
- Computer mesh codes such as MAFIA (3D), HFSS (1D and scattering matrix), and ABCI (cylindrical symmetry, easy, fast) yield very good agreement with measurements.
- For kickers different aspects are calculated with different codes: MAFIA or HFSS for impedance, EM properties using PSPICE.
- problems:

  Behavior less well understood for $\beta < 1$ in low Q structures (High Q are no problem);

  Multi-layer structures like coatings, stripes, and wire cages can be calculated using a 2-D analysis when no transitions between different types of

*Work supported by the United States Department of Energy

chambers are present. When transitions are present the problem becomes much more difficult as e.g. the case of a change of pipe radius forming a cavity or iris.

2) **Is it beneficial to have the rf shielding or vacuum chamber follow the betatron envelope?**

- Both $Z_{\parallel}$ and $Z_{\perp}$ are reduced.
- For $Z_{\perp}$, benefits, if any, are unclear.
- For $Z_{\parallel}$, required rf voltage is reduced for given energy spread, but with realistic elliptical beams in elliptical pipes naive (circular beam and pipe) estimates may be optimistic.
- For machines where the beam remains in the machine for several synchrotron periods, a reduced $Z_{\parallel}$ can lead to Landau damping of coupled bunch modes.
- Once the cage is in place significant changes in optics are no longer possible.
- Cost and reliability must be considered.

3) **What is the impedance of ceramic chambers with or without metallic strips?**

- For constant cross section low frequency impedance can be calculated with 2D electrostatic codes or analysis. With aperture changes see question 1.
- The dielectric properties of the ceramic are not important in impedance calculation.
- Metallic stripes should be sufficiently thick to shield the fields also at low frequency. This determines their surface resistivity.
- Gaps between stripes are necessary to reduce eddy currents, but should be narrow enough to avoid charge accumulation on the ceramic.
- The stripes should be made of high-conductivity metal like copper to reduce the resistive wall impedance.
- The design of the metallic stripes requires a compromise between penetration of the applied magnetic field and the need for shielding to reduce space charge impedance and static charge buildup.

4) **Is it beneficial to reduce the broad-band impedance to a few Ohm for high intensity proton machines?**

- The low frequency, inductive part of $Z_{||}/n$ leads to potential well distortion, bunch lengthening etc. via interaction with the stable bunch spectrum. This inductance may be useful in compensating the "capacitive" space charge impedance, but it is produced by ill-defined sources such as discontinuities or bellows which may also introduce resistance and resonances and thus may lead to instability.

- Steps and discontinuities like pumping ports lead to accidental cavities. Frequencies are important to ~ 3 times the beam-pipe cutoff frequency and can lead to instabilities with many nodes on long bunches.

- Higher order modes in rf cavities must be carefully measured and damped.

- It is recommended to go for a smooth vacuum chamber leading to a minimum impedance machine. In any case an accurate impedance inventory up to and beyond pipe cutoff is required.

- It is difficult and costly to shield retroactively.

5) **How do ferrite, window frame, C frame, traveling wave, and strip-line kickers compare in terms of impedance and engineering requirements?**

- Dominant parameter is the rise time requirement

  Lumped ferrite kicker preferred, has simplest construction and power supply;

  Traveling wave ferrite kicker is faster but more complex;

  Compromise - hybrid solution: lumped kicker with traveling wave power supply (IPNS);

  Strip-line kicker is very fast but expensive in power requirement $\rightarrow$ use for transverse dampers;

- General recommendations:

  Keep aperture as small as possible to minimize current/voltage, but consistent with beam size requirements;

  Kicker impedance should not drive design choice. An inductive impedance contribution is OK for operation below transition;

  If possible avoid ceramic beam tube which reduces aperture and may cause high voltage arcing;

Contra-indication: ferrite has a resistive impedance which may lead to instabilities and over-heating. If tests/calculations indicate requirement for shielding then use metallic stripes on inside a ceramic pipe.

- Impedance estimates:

  Handbook formulae for ferrite kickers are suspect/incorrect;

  No obvious difference in $Z_{||}$ for C-type and window frame designs;

  Transverse impedances differ in horizontal and vertical directions, window frame with metallic shielding strips seems preferable;

  Expect a small contribution from a strip-line damper ($\sim$ one BPM).

- Measurements are important

  Impedance measurements to assure absence of resonances;

  wire measurement at design level current to determine heating.

6) **Is it practical and/or useful to compensate the longitudinal space charge impedance?**

- Tests of inductive inserts at PSR have shown that serious longitudinal instabilities can result from high frequency resonances ($\sim$ 70MHz).
- The longitudinal coasting beam stability diagram shows a large stable region for negative inductance which can be $\sim$ 10 times greater than the simplified "Keil-Schnell" circle criterion. However, resistance may lead to instability and ferrite inserts will introduce resistance.
- For storage times shorter than the synchrotron period, as in SNS, compensation is not recommended.
- For storage times $\gg$ the synchrotron period some benefits could be realized due to increased Landau damping of coupled bunch modes.

7) **What are the best methods to measure longitudinal and transverse impedance?**

- Reliable "estimates" can be obtained if the right methods and correct interpretation are used.
- To measure narrow resonances (high Q), the best method is bead pulling, which is valid for both $v = c$ and $v < c$.

- Low and distributed longitudinal impedances (kickers, BPMs, bellows ...)

  forward transmission coefficient S21 should be interpreted with the "log-formula" and NOT treated as lumped element in a transmission line

  use smallest wire consistent with mechanical stability so $\delta Z/Z \ll 1$.

  match input and output port to 50Ω of instrument, preferably by tapered cone adaptors or with a resistive match at low frequencies. De-embedding by TSD or TRL techniques to get the impedance of the device from several scattering measurements is not easy.

  Measure device with attached transitions to beam tube as a single unit

- Low and distributed transverse impedances (kickers, BPMs, bellows ...):

  horizontal and vertical measurements require using same precautions as for longitudinal measurements;

  Single wire measurement coupled with Panofsky-Wenzel theorem is prone to error;

  "Lecher-line" (two-wire) measurement: smaller errors but requires broad-band 180° hybrid;

  Two-wire measurement easiest with 100Ω transmission line structure, note that closely spaced, narrow wires allow $\delta Z/Z \ll 1$.

- Direct measurement using a high intensity electron beam (test facility) worth considering if not too expensive.

8) **What are the key impedance issues for high power, short bunch, and low loss machines?**

- Losses in parasitic resonances can lead to significant heating by the beams with high power or short bunches.
- Compensation of space charge impedance can help to stabilize coupled-bunch modes. Naturally occurring inductances such as bellows and BPMs could be helpful, but resonant structures should be avoided (see question 4).
- A realistic impedance model - valid also at higher frequencies, not just Z/n, is required.
- Turn-by-turn simulation using macro-particles or a Vlasov equation solver should be used to predict stability limits.
- Transverse damper designers should consider the variation of bunch length throughout the cycle.

This concludes the findings of the impedance working group which were reported in the final session. The discussion of some of the points was quite animated, in particular the recommendation not to use inductive inserts for space charge compensation when additional resistive or resonant impedances are unavoidable.

In addition to answering these questions, a number of short presentations were given in the working group on related subjects:

- G. Stupakov (SLAC): Wall roughness impedance.
- H. Hahn (BNL): Coupling impedance of RHIC injection kicker.
- S. Kurennoy (LANL): Space-charge impedance in long wavelength approximation.
- J. G. Wang (ORNL): Calculation of longitudinal space-charge impedance.
- J. Dooling (ANL): Impedance calculation.
- M. Dyachkov (TRIUMF): RF screening by thin resistive layer.

In spite of their interest, the discussion of these subjects had to be kept very short due to lack of time, in particular when they had only marginal bearing on high-intensity proton machines, the topic of this workshop.